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Assessment of biomass open burning emissions in Indonesia and potential climate forcing impact

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HIGHLIGHTS

- ► Emission inventory for biomass open burning in Indonesia was conducted for 2007.
- ► Best estimates and ranges of pollutants and GHG emission were produced.
- ► Methodology for solid waste open burning emission inventory was developed.
- ► Monthly and gridded (0.25°) emissions were obtained for 3D modeling.
- ► Climate forcing associated with Indonesian biomass open burning was assessed.

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ABSTRACT

This paper presents an emission inventory (EI) for biomass open burning (OB) sources including forest, agro-residue and municipal solid waste (MSW) in Indonesia for year 2007. The EI covered toxic air pollutants and greenhouse gases (GHGs) and was presented as annual and monthly average for every district, and further on a grid of 0.25° × 0.25°. A rigorous analysis of activity data and emission factor ranges was done to produce the low, best and high emission estimates for each species. Development of EI methodology for MSW OB which, to our best knowledge, has not been presented in detail in the literature was a focus of this paper. The best estimates of biomass OB emission of toxic air pollutants for the country, in Gg, were: 9.6 SO_2; 98 NO_x; 7411 CO; 335 NMVOC; 162 NH_3; 439 PM_{10}; 357 $PM_{2.5}$; 24 BC; and 147 OC. The best emission estimates of GHGs, in Gg, were: 401 CH_4, 57,247 CO_2; and 3.6 N_2O. The low and high values of the emission estimates for different species were found to range from −86% to +260% of the corresponding best estimates. Crop residue OB contributed more than 80% of the total biomass OB emissions, followed by forest fire of 2–12% (not including peat soil fire emission) and MSW (1–8%). An inter-annual active fires count for Indonesia showed relatively low values in 2007 which may be attributed to the high rainfall intensity under the influence of La Niña climate pattern in the year. Total estimated net climate forcing from OB in Indonesia was 110 (20 year horizon) and 73 (100 year horizon) Tg CO_2 equivalents which is around 0.9–1.1% of that reported for the global biomass OB for both time horizons. The spatial distribution showed higher emissions in large urban areas in Java and Sumatra Island, while the monthly emissions indicated higher values during the dry months of August–October.

1. Introduction

The term of 'biomass open burning' generally refers to open burning (OB) of various biomass materials including forest vegetation, grass, crop residue and also municipal solid waste. OB smoke is reported to be a cause of the reoccurring transboundary haze problem in Southeast Asia (SEA) region (Koe et al., 2001). Specific weather anomalies such as those occurred during the El Niño year 1997 was responsible for most of the large forest fire events in Indonesia. The haze from forest fires in Indonesia was reported to affect regional air quality in terms of particulate matter (PM), ground level ozone and visibility locally and also in the neighboring SEA countries annually (Pentamwa and Kim Oanh, 2008).

Crop production in Indonesia generates a huge amount of residues which are commonly field burned after harvesting. OB problem is also commonly seen in most of the urban areas where municipal solid waste (MSW) is poorly managed. In the Asian developing countries and in Indonesia in particular, agriculture residue and

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MSW OB often take places in crowded areas hence can severely deteriorate air quality and cause adverse human health effects.

A proper quantification of the OB emission in the country is required in order to provide an overall assessment of the potential effects and the relevant information for formulation of appropriate mitigation measures. However, a comprehensive national emission inventory (EI) for this OB sources has not yet been reported. Although several global or regional EI databases also provided emission estimates for Indonesia they are not necessarily up-to-date nor have been developed using the detailed local activity data and relevant emission factors (EFs) suitable for the country. Several available global databases, for example, were compiled using the amount of biomass burned obtained from extrapolation of local data and partly from satellite data. The updated Global Fire Emission Database (GFED) provided long-term seasonal and gridded emissions of OB (i.e. deforestation, savanna, forest fire, and agricultural waste burning) using different satellite products (Van der Werf et al., 2010). Streets et al. (2003) conducted an EI for regional studies of forest fire and agriculture residue burning using statistics data for the 1950s–1990s and the total emissions were spatially distributed using Advanced Very High Resolution Radiometer (AVHRR) fire counts to produce the gridded dataset (1° resolution). Likewise, long-term seasonal and gridded emissions of non-agricultural open fires for Asia was developed by Song et al. (2010) using MODIS (Moderate Resolution Imaging Spectroradiometer) burned area product (MCD45A1) at a resolution of 500 m, considering geographical variation and country specific fuel load data. None of the reported studies have reported the emission estimate for MSW OB.

This study aimed to provide detailed emission database of OB in Indonesia for the year of 2007. The biomass OB included forest fire, crop residue field burning and MSW OB. Step-wise activity data collection and analysis for the rigorous selection of relevant EFs are presented. EI for multiple gaseous species (NO_x, SO_2, CO, NMVOC, and NH_3), primary particles (PM_{10}, $PM_{2.5}$, BC, OC), and GHGs (CO_2, CH_4, and N_2O) was conducted. The uncertainty analysis was conducted and the EI results were presented as the low, high and best estimates. The climate forcing effect introduced by the OB was assessed using the global warming potential (GWP) metric. Further, monthly emissions and the gridded ($0.25° \times 0.25°$) emissions suitable for three-dimensional modeling purposes were prepared.

2. Methodology

For emission estimation, this study used the general framework and emission calculation equations adopted from the Atmospheric Brown Cloud Emission Inventory Manual (ABC EIM) (Shrestha et al., in press) which are summarized in Fig. S1, Supplementary Information (SI).

2.1. Emission factors

The variation range of emission factors (EFs) and the variation in activity data were used to analyze the EI uncertainty, i.e. to produce the low, high and best emission estimates for each species. The lower and higher values of the compiled EF ranges were used to determine the low and high estimates, respectively, while the determination of the "best estimates" for the EF was similar to that used in Thongchai and Kim Oanh (2010). Accordingly, for the agricultural residue OB, whenever available the EFs for specific type of crop/land cover were used; otherwise EF for general crop residues (combined crops) was used. The EF values measured for the sources in Indonesia were the first choice, followed by values generated for similar biomass types and open burning practices in the Asian region. If there were no data available for the Asian region, relevant data from other parts of the world were used. Range of EFs for major crop residues OB used in this study is compiled in Fig. S2, SI.

Due to the lack of the local EF measurement data for forest fire and savanna OB, compiled data in Andreae and Merlet (2001), Van der Werf et al. (2010) and Akagi et al. (2010) were used. Furthermore, it was reported that most of fires occurred in Indonesian peatland swamp forest were due to land-clearing for agriculture land (deforestation). However, EFs specific for peatland swamp forest (above ground biomass) fires are not readily available in the literature. Therefore, most of EFs were taken from Van der Werf et al. (2010) under the deforestation fire category except for four species (CO, NH_3, CO_2 and CH_4) which were taken from the peat soil emission EF measured locally in Kalimantan (Borneo), Indonesia (Christian et al., 2003). Accordingly, for these four species (CO, NH_3, CO, and CH_4) the estimation may be conservatively high as the EFs are more suitable for below surface peat soil burning. The EFs used in this study are summarized in Table S1, SI. Not many literature sources reported EFs from MSW OB, therefore the EFs given in AP-42 (US EPA, 1995) and by Akagi et al. (2010) were used which are also presented in Table S1, SI.

For the QA/QC purpose, the mass balance check was done to ensure that the selected EFs satisfied the conditions of $PM_{2.5} \leq PM_{10}$ and $BC + OC < PM_{2.5}$.

2.2. Activity data

2.2.1. Forest fire

Active fire count data are commonly used to estimate the forest burned area (fire) for both global and regional scales with varying success. To reduce the uncertainty related to fires with a size well below a pixel of a hotspot (1 km^2), the MODIS (Moderate Resolution Imaging Spectroradiometer) burn scars product (MCD45A1) was used in our study. This product was downloaded from http://modis-fire.umd.edu/ and was analyzed with the land cover map to derive the burned area. A step-wise data extraction and processing procedure is presented in Fig. S3, SI. The national land cover map for the year 2005 was obtained from the 'Glob Cover' archive with a resolution of 300 m (http://www.iscgm.org/cgi-bin/). The dataset with original Land Cover Classification System (LCCS) legend was then re-classified into 6 broad types of vegetation susceptible to burning in Indonesia (primary tropical forest, secondary tropical forest, savanna, shrubland, mangrove, and peatland swamp forest). MODIS MCD45A1 was overlaid with the land cover map and the number of burn scars was determined for each district (within the district administration boundary).

The above ground dry matter density (fuel load in tonne per hectare, t ha^{-1}) is important activity data but it varies significantly with the type of vegetation and geographical location. We used the measurements data for Sumatra and Kalimantan forests reported by Murdiyarso et al. (2002) of 14.7–93.6 t ha^{-1} with the best estimate of 16.8 t ha^{-1} for the primary forest and 37.8–54.8 t ha^{-1} with the best estimate value of 38.2 t ha^{-1} for the secondary forest. The values were somehow lower as compared to the values reported for tropical forest in Thailand, 48–90 (primary) and 75–80 (secondary) t ha^{-1} (Piyaphongkul et al., 2011). Murdiyarso et al. (2002) also reported the typical value for Borneo mangrove and peatland swamp forests of 128 t ha^{-1}. This study also used the typical value of 0.6 t ha^{-1} for savanna and shrubland (14.3 t ha^{-1}) that was obtained from the measurements for Kalimantan (Christian et al., 2003). The best estimate values of burning

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